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Using MIMO Techniques to Enhance Communication Among Static and Mobile Nodes in Wireless Sensor Networks

Marco A. M. Marinho[§], Edison Pignaton de Freitas[§,*], João Paulo C. Lustosa da Costa[§], André Lima F. de Almeida[#] and Rafael Timóteo de Sousa Júnior[§]

[§]Department of Electrical Engineering, University of Brasília, Brasília, Brazil.
marco@aluno.unb.br, {edisonpignaton, jpdacosta, desousa}@unb.br
*Brazilian Army Technology Center, Brazilian Army, Brazil.
[#]Teleinformatics Engineering Department, Federal University of Ceará, Brazil. andre@gtel.ufc.br

***Abstract*— Wireless sensor networks are evolving to hybrid networks in which static and mobile sensor nodes cooperate in order to address challenging requirements imposed by new emerging applications. However, due to the ad hoc nature of the network and especially to resources constraints of the sensor nodes, this cooperation is not trivial, requiring a number of retransmissions thus wasting precious resources. In this paper the use of cooperative multiple input multiple output (MIMO) techniques is proposed to overcome transmission problems, ensuring a reliable and more efficient communication link with less retransmissions. Extensive simulation experiments support the proposal, and the results highlight the benefits in using MIMO to deliver messages from static to mobile nodes in wireless sensor networks.**

Keywords - wireless sensor networks; cooperative multiple input multiple output; energy efficiency

I. INTRODUCTION

A number of emerging applications using wireless sensor networks (WSN) are appearing, in which the interoperability of static and mobile sensor nodes is remarkable [1]. WSN composed of static and mobile nodes have different applications, from surveillance systems used in the military, to optimized fertilizers spreading in high precision agriculture. Mobile sensor nodes in these types of systems are usually robotic platforms moving on the ground (Unmanned Ground Vehicles - UGVs) or above it (Unmanned Aerial Vehicles - UAVs), which can act as mobile sinks depending on the applications. On the other end, static sensor nodes are usually small platforms with constrained processing and energy resources, which collect data and send to the mobile nodes.

Regarding the static sensor nodes, an important concern is the energy consumption, since these nodes are usually supported by batteries, which limits their energy budget. Additionally, these sensor nodes are usually deployed in areas that are difficult to be accessed, thus making impractical, or even impossible, the replacement of such energy resources. This means that once the battery is depleted, the node is lost. As the number of nodes facing this situation raise, a network becomes compromised. To overcome such problem, smart energy resource management is needed to extend the network lifetime.

Communication among static and mobile sensor nodes is highly prone to errors, especially due to the ad hoc nature of the network. Mobile nodes change their positions frequently, which results in many lost packets, thus requiring retransmissions. Considering that performing transmissions is the most energy consuming task for the static sensor nodes [2], it is highly desirable to reduce the number of retransmissions so as to reduce energy depletion.

Observing this dual problem regarding energy resource usage and its correlation to communication efficiency, a promising solution is to improve the quality of the communication link so that the number of retransmissions can be reduced. In [3] an approach that explores a cooperative multiple input multiple output (MIMO) strategy is proposed to address the problem of long distance communications in WSN exclusively formed by static nodes. In this paper the approach presented in [3] is extended to address the communication problem among static and mobile sensor nodes. The kernel idea of this proposal is to explore the local interaction among the static sensor nodes to deliver their messages in a more efficient way to the mobile sensor nodes. Achieving this goal, the number of retransmissions can be reduced, relieving the demand for energy, thus extending the sensor nodes and consequently the entire network lifetime.

The paper is organized as follows: Section II presents related work in the area. Section III describes the cooperative MIMO technique. Section IV presents and discuss simulation results, then Section V concludes the paper.

II. RELATED WORK

Multiple input multiple output (MIMO) systems can operate under specific performance requirements related to bit error rate and transmission rate for a given energy budget if compared to a conventional system. This is an area of active research due to the potential presented by multi-antenna systems to increase the capabilities of channels with fading [4].

The use of MIMO has been studied for spatial diversity and multiplexing gain to enhance the energy efficiency of WSNs. In [5] the authors propose techniques for energy efficient communication aiming at to diminish the total energy consumed both in transmission and in the processing performed by single input single output (SISO) systems. In [6] the increase in the overhead involved in the training of the MIMO systems is studied. In [7] the efficiency in the cooperative transmission of space-time block codes (STBC)

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is analysed. All these referred works present studies related to WSN composed exclusively of static sensor nodes, while the approach presented in this paper addresses the scenario including mobile sensor nodes in the network.

In [8], a MIMO technique is proposed for data collection from sinks in a WSN. The authors present an approach in which polling stations are used to intermediate the communication between the mobile node and the MIMO cluster, along a predefined path for the mobile sink. In relation to our work, the two main differences are the presence of polling stations in their proposal, which is not required in our approach, and their dependence on a predefined path for the mobile sink movement, a limitation that does not exist in our approach, which considers several mobile sensor nodes following a random movement pattern.

III. Efficient Transmissions from Static to Mobile Nodes Based on Cooperative MIMO

Taking advantage of the cooperative nature of the sensor networks operation, cooperative MIMO can be introduced in these systems to provide reliable communications among static and mobile nodes, by diminishing the link breakage ratio, thus possibly requiring less energy resources. Instead of a conventional arrangement of multiple antennas in a single sensor as in the traditional MIMO, in cooperative MIMO systems, multiple sensors cooperate to transmit and receive data. Figure 1 presents an example in which two clusters of sensors establish a communication to a mobile node as a MIMO system. The black circles represent static sensor nodes, while the aircraft represents the mobile node. The circles evolving static sensor nodes represent that those sensors form a cluster.

Notice that the term “cluster” used to describe the situation in Figure 1 has not the same meaning that it usually has in WSN research field. In Figure 1 there is no difference among the sensor nodes, and the term “cluster” is used to identify a group of cooperating sensor nodes, it does not refer to a group of sensors represented by a leader (cluster-head).

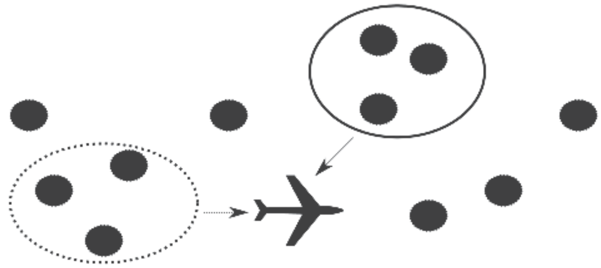

Figure 1. Cooperative MIMO communication between clusters of sensors and a mobile sensor.

In the cooperative MIMO arrangement sensor nodes could cooperate to transmit different symbols at the same time slot to achieve higher data rates, or, with proper pre-coding, cooperate transmitting the same symbol to achieve higher power at the front end of the receiver. Using this approach, if two sensors near to each other cooperate to transmit information, the efficiency is effectively doubled, as two symbols can be transmitted over the same time slot.

Figure 2 presents the generalization of the idea for a MIMO systems composed of Q transmitter sensors and P receiver antennas (Q by P MIMO), while Figure 3 presents a schematic example of 2 by 1 MIMO, i.e, a single input multiple output (MISO), which is the type of cooperative MIMO used in this paper proposed approach.

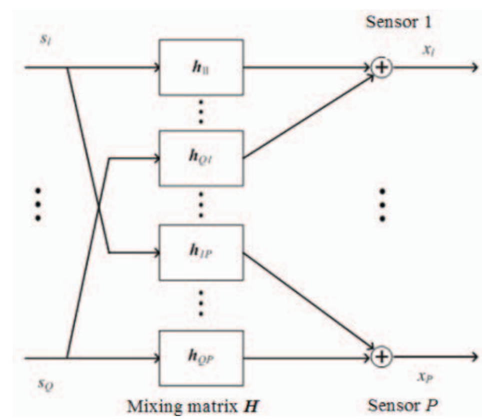

Figure 2. General case – MIMO system Q transmiters and P receivers

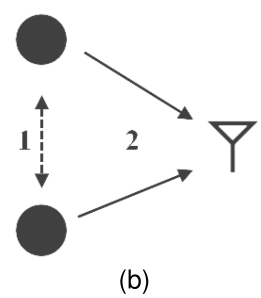

Figure 3. Example of a 2 by 1 MIMO system, also known as multiple input single output (MISO) system

Considering the MIMO system in Figure 2, the communication channel between the i-th transmitter sensor to the j-th receiver sensor is given by $h_{i,j}$. The output of the j-th antenna $x_j(n)$ is given by:

$$x_i(n) = \sum_{i=1}^{Q} h_{i,j} s_i(n) \quad (1)$$

where $s_i(n)$ is the transmitted symbol at the n-th time instant by the i-th source.

Note that (1) can be rewritten in the matrix form as follows:

$$\boldsymbol{X} = \boldsymbol{H}\boldsymbol{S} \quad (2)$$

The original transmitted symbols can be recovered in two steps. In the first step given $\boldsymbol{X}$ and $\boldsymbol{S}$, (2) can be solved, finding $\widehat{\boldsymbol{H}}$, which is an estimate of $\boldsymbol{H}$. The symbol matrix $\boldsymbol{S}$ contains the pilot signals. For low Signal-to-Noise Ratio (SNR), the estimation of $\boldsymbol{H}$ can be severely degraded.

After the channel estimation stage, in the second step the Q transmitter sensors send unknown symbols, which are estimated by using $\widehat{\boldsymbol{H}}$ and (2). Then, from this step, $\widehat{\boldsymbol{S}}$ is obtained, which is an estimation of the transmitted symbols.

In the example presented in Figure 3, the numbers indicate the sequential order of the events, first the transmitting sensors exchange the information that needs to be transmitted, and then both sensors transmit different symbols at the same time slot to the receiver.

IV. Experiments and Results

A. Studied Scenario and Simulation Setup

The scenario used as case study is an area surveillance system, in which static sensor nodes on the ground cooperate with mobile sensor nodes in the air, i.e. Unmanned Aerial Vehicles (UAVs). The static sensor nodes are supposed to have simple sensing capabilities, such as movement, temperature or pressure, while the UAVs carry more sophisticated sensors, such as visible light or infrared cameras. In this system, the static sensor nodes are assigned to detect certain events of interest and send messages to the UAVs. Based on the received data, the UAVs decide the significant events, flying to the place where they happened to collect additional information with their sophisticated sensors.

For the simulations, an area of 10 km × 10 km is filled with 4500 nodes, each one presenting a 350 m communication range. The nodes' positions are randomly generated following a two dimensional independent uniform Poisson distribution process. For these values and distribution, the probability that a given node will have at least one neighbor within a distance less than 350 m is given by [9]:

$$P(x > 1) = \left(1 - e^{-d\pi r^2}\right)^n \quad (3)$$

where P is the probability that any node has at least x neighbors in a radius of r meters around it, d is the node density and n is the total number of nodes in the area.

In this scenario, the achieved node density results in an approximately 99.9 % probability of any node having at least another node within a 350 m radius. The relatively small distance between the sensors is needed to guarantee that the MIMO technique is energy efficient. If the sensors were far apart, too much energy would be spent in the communications necessary to share the packets across the nodes (step 1 in Figure 3) due to the high power needed to transmit over large distances.

Packets are generated across the network with a rate of 4 packets per second and the node generating the packet is chosen following a discrete uniform distribution. The high packet generation rate is chosen to guarantee that the network always presents a packet to be transmitted to each UAV.

The packet transmission priority follows the order of arrival, the older the packet the highest transmission priority is assigned to it. Ten UAVs are distributed in the area with their initial positions randomly chosen using a uniform distribution process. These nodes move according to the Random Way Point (RWP) mobility model and for each way point a random speed is chosen between 70 km/h and 100 km/h.

Figure 4 presents the simulated scenario. The dots on the bottom of the figure represent to static sensor nodes on the ground, while the slightly bigger ones on the top represent the UAVs.

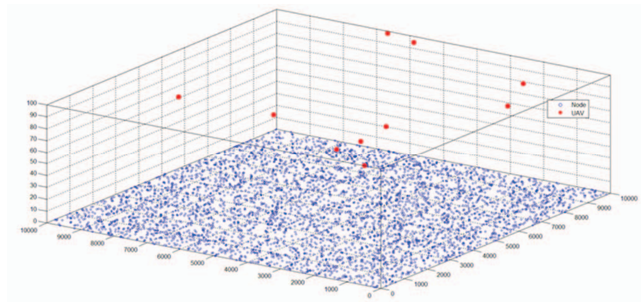

Figure 4. Tridimensional view of the simulated scenario.

The transmission time of a packet (the required time window to transmit a packet) varies from 1 to 15 seconds. The transmission time is composed of the initial handshake process, actual data relay, and the final ACK from the UAVs. Note that transmission rates in WSNs are usually very low, with 2000 kb/s being considered a very high rate, and only achievable at small distances between nodes under low SNR. Rates ranging between 80 kb/s - 250 kb/s are typical data rates for WSNs in operation today [10] [11]. At 100 kb/s a 1.5 Mb packet would take approximately 15 seconds to be transmitted; Exchanging audio or video demand large amounts of data to be transmitted with varying quality degrees (depending on the user application), with a 128 kbps audio file having about 1 Mb per minute of recorded audio. With lower transmission rates, larger transmission time windows are needed to achieve the same amount of data relayed to a UAV. Notice that in some cases it might not be practical to spread the information across multiple small packets delivered to different UAVs. This is the case, for instance, in which the UAVs would have to make decisions among possible options based on the received data, e.g. photograph an area or select new waypoints to the destination.

The maximum communication distance between a UAV and a MIMO cluster is 550 m. If the distance is larger than this value at any moment during communication, it is considered that the packet failed to be delivered, since at long distances the BER will be too high. The node will try to retransmit this packet as soon as a UAV is available again with a priority related to the moment it was generated on the network. Each simulation runs for a total of 3600 seconds. For each simulation the number of packets successfully transmitted to the UAVs is measured as well as the number of failed transmissions, i.e. packets that are not delivered. Simulation parameters such as the positions of nodes and movements of UAVs, packet generation time and destination are kept the same across all simulations so as to preserve the same scenario for the sake of comparisons between the obtained results. By the way, these results, presented and discussed hereafter, represent the average of 30 Monte Carlo runs for each setup.

B. Results and Discussion

Firstly the simulation results are analyzed regarding the shortest time window required to transmit a packet. Figure 5 shows a comparison concerning the numbers of successfully transmitted packets versus the amount of nodes in a MIMO cluster, observing that in a cluster with only one node it is impossible to configure a cooperative MIMO (highlighted with a star symbol "*").

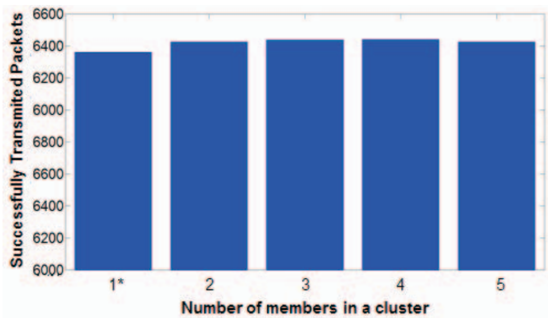

Figure 5. Successfully transmissions at 1s transmission time.

As depicted in Fig. 5, by increasing the number of member nodes in the MIMO cluster, there is no significant improvement in the number of successful transmissions. Due to the very short time window required to perform a transmission, all the packets generated across the network can be successfully transmitted. Additionally, the usage of the Cooperative MIMO does not cause any negative impact on network throughput. However, although the number of cluster members has a small impact on the amount of transmitted packets, there is a remarkable difference in the amount of failed transmissions, as shown in Figure 6.

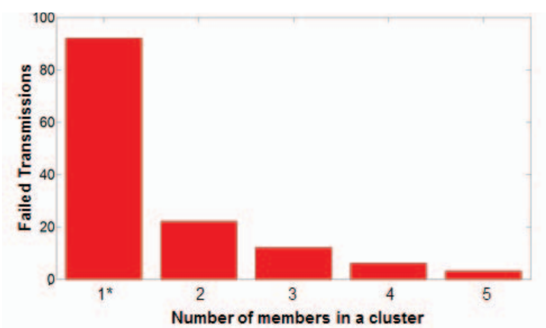

Figure 6. Failed transmissions at 1s transmission time.

Even if a very short time is needed to perform a transmission, the Cooperative MIMO yields a significant reduction in the number of failed transmissions across the network.

Based on these numbers of successful and failed transmissions, it is possible to establish a transmission cost for a certain WSN configuration, defined as the amount of retransmissions needed to achieve one successful transmission.

$$Cost = \frac{Failures}{Successes}$$

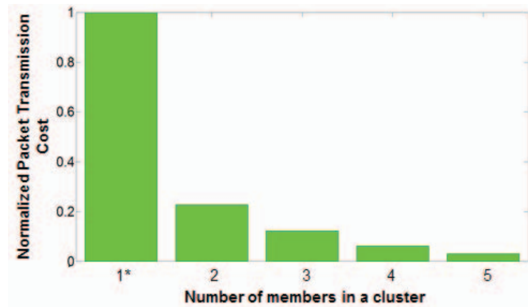

Figure 7. Normalized transmission cost at 1s transmission time.

From Figure 7 it is possible to observe that even for fast transmissions the Cooperative MIMO reduces the transmission cost to about 20% of the case with no cooperative MIMO. This result directly impacts the energy savings across the entire network, as for most WSNs the communication is the most expensive task in terms of energy consumption. This implies in increased network lifetime without reducing the amount of transmitted data.

Now comes the discussion concerning the impact of Cooperative MIMO on transmissions that require longer time windows to be performed. In this case, as most WSNs present low transmission rates [10][11], a link has to be maintained for a long time so that data could be successfully transmitted. The results for the case in which 7 seconds are needed for each transmission is presented in the plots of Figures 8, 9 and 10. The cost is reduced to 11% when compared to the case where no Cooperative MIMO is used and the throughput is almost doubled by using two nodes working with the Cooperative MIMO. This allows twice as much data to be transmitted at a much lower energy cost than what would be possible in a non-cooperative network.

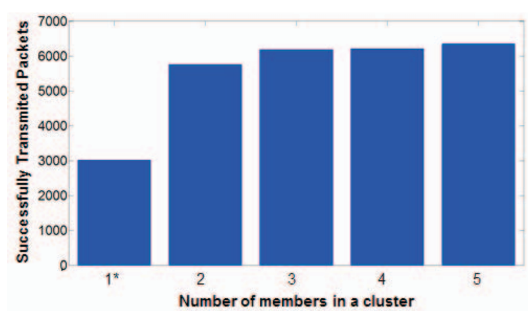

Figure 8. Successfully transmissions at 7s transmission time.

For the case in which 15 seconds are needed to transmit a packet, the results are shown in Figures 11, 12 and 13. In this case transmission without the use of Cooperative MIMO is practically impossible, and a larger number of cluster members is necessary to achieve good throughput and cost of transmission on the network. The results show that the technique allows the network to function at costs approximately 12 times lower with 4 members on each cluster. This means that it allows networks with very low transmission rates to transmit to mobile nodes moving at considerably high speeds.

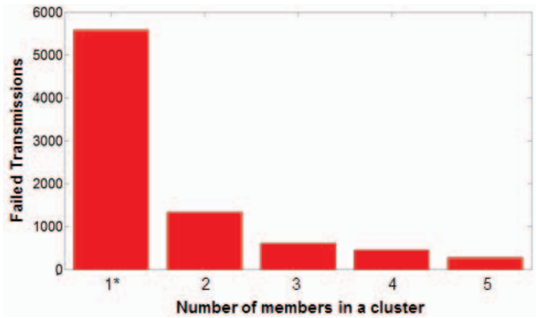

Figure 9. Failed transmissions at 7s transmission time.

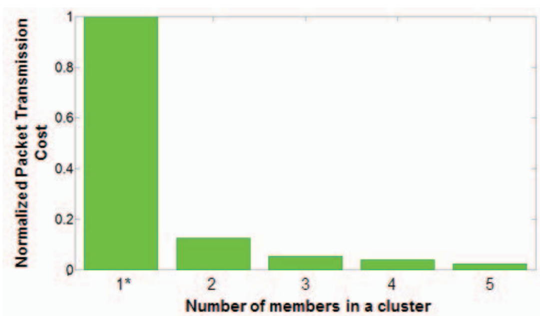

Figure 10. Normalized transmission cost at 7s transmission time.

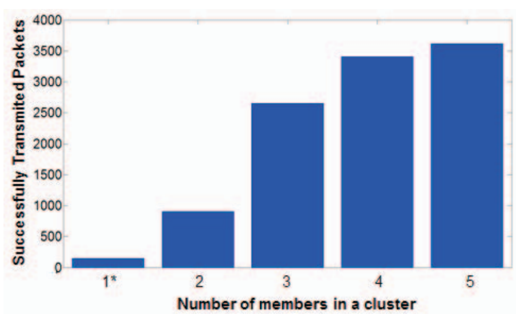

Figure 11. Successfully transmissions at 15s transmission time.

Besides the question of successful transmissions it is interesting to analyze the possible increase in latency across the network, since the packets need to be spread among the MIMO cluster members before they can be transmitted to the UAVs. Figures 14 to 16 show that this is not the case because, if the Cooperative MIMO is not used, the amount of retransmissions needed results in a higher latency than that caused by spreading the packets to perform the communication using MIMO.

The delay comparisons presented in Figures 14 to 16 represent the end to end delay, which is the elapsed time between the start in transmitting a packet and the time of this packet arrival at its destination node, i.e., one UAV. This measure includes the time waiting for retransmission, in case of transmission failure, and also the time for sensor nodes synchronization when using cooperative MIMO configurations.

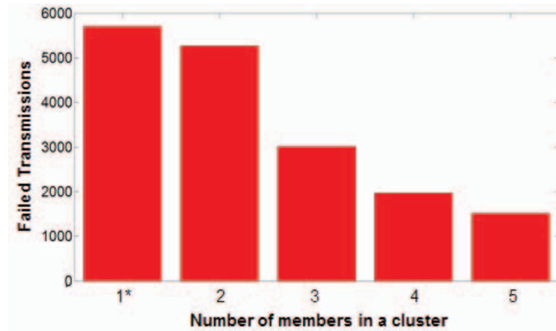

Figure 12. Failed transmissions at 15s transmission time.

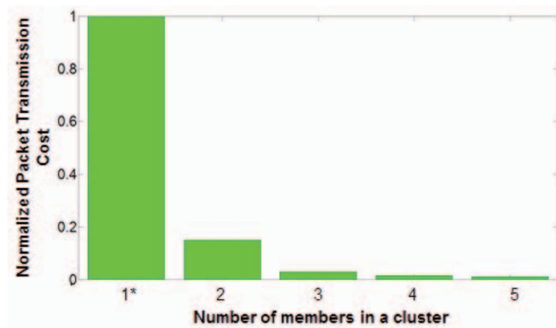

Figure 13. Normalized transmission cost at 15s transmission time.

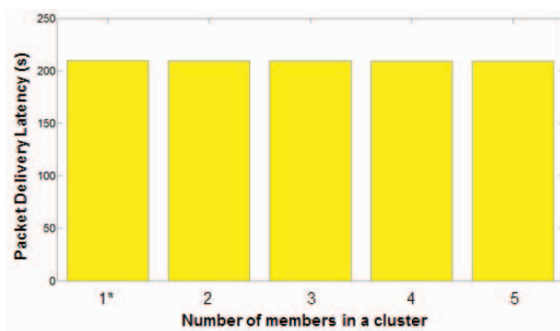

Figure 14. Delay at 1s transmission time.

At very short transmission time windows, a very small positive effect on the delay is observed, since failed transmissions do not occupy the UAVs long enough to have a significant impact on the average network delay. However for longer transmission time windows, there is a significant positive effect since failed transmissions will keep UAVs occupied for much more time, thus making packets wait for opportunities to be transmitted.

Finally, it is interesting to consider the energy consumption of the different setups. Table I shows that reducing the number of retransmissions comprehensively outweighs the extra energy necessary to spread the packet among the cluster members in the Cooperative MIMO configurations. As the transmission in non-cooperative networks is always the most expensive in terms of cost, it represents the standard cost to which all other configurations are compared. In Table I, the results for the transmission times are presented over the columns and cell values represent the relative transmission cost for each successful transmission compared to the case of non-cooperative networks. Energy consumption data is based on the Berkley MICA2 Mote figures [12].

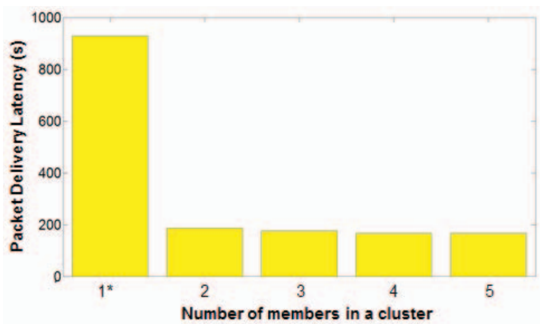

Figure 15. Delay at 7s transmission time.

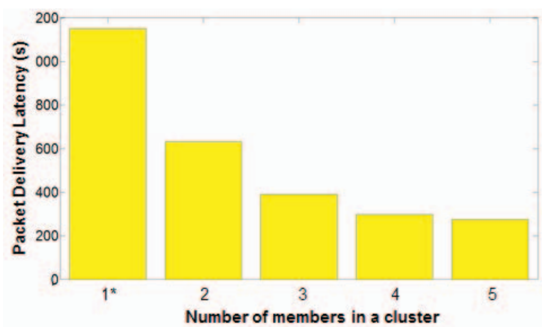

Figure 16. Delay at 15s transmission time.

TABLE I. ENERGY CONSUMPTION

Maximum Number of MIMO Cluster Members	**Time required to transmission (s)**		
	1	***7***	***15***
1 (no MIMO)	100%	100%	100%
2	25.69%	14.09%	16.91%
3	15.42%	6.67%	3.67%
4	8.47%	5.40%	2.06%
5	4.67%	3.53%	1.63%

The results presented in Table I show that even for short transmission times it is possible to achieve energy efficiency four times larger with the usage of only two nodes on the MIMO cluster. The increase in energy efficiency lessens as the number of member nodes grow: the more members in a cluster the less effective it is to add more members. The extra energy efficiency attained might not compensate the extra complexity necessary for implementing the MIMO transmission over a large number of nodes, or the extra number of nodes that need to be added to a network so that the node density is enough to produce clusters with a large number of members. However, this depends on the specific system requirements.

V. CONCLUSION

This paper presents an approach to reduce energy consumption in hybrid WSNs. Our simulation results corroborate that the proposed Cooperative MIMO technique is able to achieve higher efficiency in delivering messages from the static to the mobile nodes. It is possible to obtain a better relation of failed transmissions per successful transmissions while increasing the amount of data that can be transmitted across the network. This improved efficiency reduces energy usage due to communications, which contribute to increasing the network lifetime. The technique also provides a significant decrease in the mean packet delivery delay across the network. Future works are planned to make the MIMO clusters adaptable in presence of obstacles in the environment.

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